PERCHLORATE CONTAMINATION TREATMENT ALTERNATIVES

D R A F T

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BACKGROUND

Sources of Contamination. Perchlorate contamination problems in California are mainly the result of past unregulated discharges of ammonium perchlorate (NH_4ClO_4) from rocket fuel manufacturing plants or demilitarization of missiles. Ammonium perchlorate is primarily used as an energetics booster or oxidant in solid propellants. The ammonium ion initially present in the groundwater at contaminated sites has generally biodegraded over time. Another source of perchlorate contamination is potassium perchlorate ($KClO_4$) which is used as a solid oxidant for rocket fuel as well as for other purposes such as pyrotechnics, flares and airbag ignitors.

Chemistry. The perchlorate anion (ClO_4^-) in its salt form is extremely soluble in both water and polar organic solvents. It is exceedingly mobile and persistent in groundwater under typical environmental conditions. Perchlorate is very slow to react and cannot be reduced with common reducing agents or be precipitated using commonly available treatment reagents (i.e., common cations).

Drinking Water Standard. There is currently no state or federal drinking water standard for perchlorate. SB 1822 (Sher), signed by Governor Davis September 8, 2002, requires that the Department of Health Services (DHS) adopt a maximum contaminant level (MCL) for perchlorate in drinking water by January 1, 2004. Until an MCL is in place, DHS uses a 4-microgram per liter (µg/L) advisory action level to protect consumers from adverse health effects of perchlorate. The 4 µg/L concentration corresponds to perchlorate's current detection limit.

TREATMENT TECHNOLOGIES

Most standard physical and chemical water and wastewater treatment processes are not generally applicable to remove or destroy the perchlorate ion. Available treatment alternatives that only remove the perchlorate ion require additional steps to treat or dispose of the concentrated perchlorate residual wastestream that is generated. Technologies that have been successfully used to treat perchlorate contamination have primarily involved anion exchange to remove the perchlorate ion, or biological treatment to reduce perchlorate to the chloride ion (Cl^-) and elemental oxygen (O_2). Other removal technologies such as granulated activated carbon (GAC) and membrane filtration have had limited application. Chemical reduction processes to destroy the perchlorate ion have been developed to treat the concentrated brines generated from ion exchange and membrane filtration processes but have had limited application. Additional chemical reduction processes for contaminated groundwater are being researched. Lastly, there has been some research in the area of phytoremediation which may only have limited application in the future.

Specific treatment alternatives that have been implemented full-scale, demonstrated or are being researched are described below:

ION EXCHANGE

Anion exchange technology is the most commonly used physical chemical treatment method for perchlorate contamination. Anion exchange resins are commercially available to remove the perchlorate anion from aqueous wastestreams. A major concern with the use of ion exchange is the resultant brine wastewater that is high in both perchlorate and total dissolved solids (TDS), and must be disposed or somehow treated.

Ion exchange capacity for perchlorate is significantly reduced when treating waters with high total dissolved solids and especially with waters high in sulfates (each double negatively-charged sulfate ion will replace two chloride ions). In these cases more frequent regeneration of the resin bed is required and may not be cost-effective. Because perchlorate has ion exchange properties similar to nitrate, nitrate selective resins that were developed to preferentially exchange nitrates over sulfates are generally used to remove perchlorate. These selective resins prevent sulfates from displacing or "dumping" nitrate or perchlorate as the bed reaches saturation.

Full-scale systems for treatment of contaminated groundwater for drinking water and remediation include:

- *La Puente Valley County Water District, CA.* In December 1999, the Department of Health Services accepted the Calgon ISEP® (Ionic SEParation) technology for use in removing perchlorate from drinking water source waters. *A* 2500 gpm system designed to treat 600 µg/L of perchlorate began operating in February 2000. The system operates 19 hours/day to control the perchlorate plume in the San Gabriel Groundwater Basin. Perchlorate concentrations (~200 µg/L) are treated to below the 4 µg/L action level.
- *Kerr-McGee, Henderson, Nevada*. Since November 1999 a 450 gpm Calgon ISEP® ion exchange system has operated to treat perchlorate containing seep water draining into Lake Mead. Actual flowrates varied between 200 to 560 gpm with 80 to 110 mg/L perchlorate levels treated to non-detectable (<2 mg/L using an ion selective electrode). Maintenance problems are associated with high TDS, hardness, and sulfate concentrations.
- *Lawrence Livermore National Laboratory - Building 834, Site 300.* Three anion exchange systems using a nitrate selective resin (SYBRON IONAC SR-7) were installed and began operating in 2000 to treat low concentrations of perchlorate (~10 µg/L) in extracted groundwater to below 4 µg/L. In these systems, anion exchange is part of a treatment train, preceded with biological treatment to remove nitrate and followed with granular activated carbon to remove TCE. Flowrates of the three systems range from 1000 gpd to 5000 gpd.
- *City of Monterey Park Delta Treatment Plant (San Gabriel GW basin).* A 4,500 gpm ion exchange treatment system is proposed. The comment period for CEQA notice for a negative declaration ended in January 2003. As of April 2003, construction of the treatment plant had yet to be initiated.

Bi-Functional Resins

Oak Ridge National Laboratory (ORNL) and the University of Tennessee have recently developed bi-functional anion exchange resins that are highly selective for perchlorate. The technology has been licensed to Purolite to develop a commercial version of the resin. The bi-functional resins consist of quaternary ammonium groups with large (C6) and small (C2) alkyl groups resulting in high selectivity and good exchange kinetics. The ability to select for perchlorate and not remove other anions means a significantly greater resin capacity for perchlorate. Additionally, the chemistry of the extracted groundwater is not negatively altered by the removal of other ions which can cause the treated water to be corrosive. Bi-functional resins are currently very expensive and can cost $1500/ft^3$ as compared to $200/ft^3$ for other anion exchange resins that are being used to treat perchlorate.

Difficulty with regeneration of bi-functional resins has limited their use. ORNL has patented a process using a ferric chloride-hydrochloric acid displacement technique to regenerate bi-functional and other selective anion-exchange resins. Lab studies indicate a high recovery of ion-exchange sites can be achieved with the regenerant solution without affecting the resin's performance after repeated cycles. Projects involving bi-functional resins include:

- *Edwards AFB.* The ORNL bi-functional resin treatment system, including a chemical regeneration process was successfully demonstrated at Edwards AFB, Site 285 on groundwater with 50 µg/L perchlorate. Tests on the 1 gpm system (2 bed volumes/minute) indicated that the bi-functional resin was able to treat over 100,000 bed volumes before a breakthrough of 5 µg/l perchlorate occurred. Construction of a full-scale treatment system incorporating the bi-functional resin began in October 2002 and is expected to become operational in 2003.
- *Stringfellow Site*. A full-scale 25 gpm ion exchange bi-functional resin test unit to treat the downgradient "toe" of the perchlorate plume (~30 µg/L) is planned for September 2003. The resin, highly selective for the perchlorate, is expected to last several months before changeout is required. On-site regeneration was not an option because of location in a residential area which required a low profile and minimal operational requirements. High TDS, including sulfates (~200 mg/L) and nitrates (~70 mg/L), makes use of non-selective anion exchange resins problematic for this specific application due to frequent regeneration or changeouts, and no brine disposal options.

Brine Treatment

The brine from regenerating an anion exchange resin bed contains high concentrations of perchlorate as well as high total dissolved solids (TDS). The brine stream may range from 1% to 5% of the volume of contaminated water treated, but is usually in the range of 1 to 2%. Approximately 10 pounds of salt is used to regenerate each cubic foot of resin. Technologies to treat the concentrated regeneration brine include:

- *Calgon ISEP+™ System*. The perchlorate and nitrate destruction module (PNDM) of this system is a catalytic chemical reduction process for treating perchlorate and nitrate

ions in the waste regeneration brine. In this process, ammonium (a hydrogen source) is added as a reductant, and perchlorate is reduced to chloride ($NaClO_4 + 8\ H^+ = NaCl + 4\ H_2O$). The system operates at 250º C and is relatively energy intensive. NASA (JPL Pasadena) sponsored a seven month pilot study of an ISEP+™ system prototype during 1998-1999 on groundwater with 1200 µg/L perchlorate and high concentrations of nitrate and sulfate. Perchlorate was treated to non-detectable (< 4 µg/L), and nitrates and sulfates were removed to acceptably low levels. The PNDM effectively reduced the perchlorate and nitrate present in regeneration brine waste, while greater than 96% of the sulfate was removed. The treated regenerant stream was reused (i.e., recycled) to effectively regenerate the resin. The overall process waste from the system was about 0.16% of the feed volume. O&M costs are estimated at about two times the cost of a comparable biological treatment unit.

- *Oak Ridge National Laboratory*. ORNL has developed a method to degrade perchlorate in $FeCl_3$-HCl regenerant solutions using ferrous iron and/or non-toxic organic reducing agents (US patent pending). Results indicate that complete destruction of perchlorate to chloride and water can be achieved in less than one-hour residence time. While perchlorate is reduced, ferrous (Fe^{++}) ions are oxidized to ferric (Fe^{+++}) ions, which replenish or "regenerate" the $FeCl_3$ - HCl solution.
- *Applied Research Associates - Integrated Thermal Treatment Process.* Laboratory research demonstrated that perchlorate in regenerant brine could be thermally decomposed at elevated temperature and pressure with the addition of reducing agents and promoters. Concentration of the brine with reverse osmosis would be necessary to make the process cost-effective. A patent application is pending.

BIOLOGICAL REDUCTION PROCESSES

Perchlorate can be anaerobically biodegraded under reducing conditions. In these reactions, perchlorate serves as an electron acceptor and is readily reduced to water and chloride in the presence of an appropriate food source (electron donor) and redox conditions. A number of microorganisms have been identified that have the capability to reduce both perchlorate and chlorate. Most identified bacterial strains that reduce perchlorate are denitrifying facultative anaerobes. Not all denitrifying bacteria can reduce perchlorate however, and in some cases the presence of nitrate can inhibit perchlorate reduction. Many reactor types have been investigated for perchlorate removal. Most of these systems are attached growth reactors using either granular activated carbon (GAC) or sand, and are able to remove perchlorate to very low levels. A variety of electron donors including ethanol, methanol, acetate, hydrogen and cheese whey have been utilized in these reactors. A total dissolved solids concentration above 20,000 to 30,000 mg/L generally inhibits perchlorate reduction. Microorganisms from saline environments may be able to degrade perchlorate at up to 5% salt concentrations. Fluidized bed reactors (FBR) as well as packed bed reactors (PBR) have been developed for treating perchlorate contamination and are commercially available.

In April 2002 the DHS Water Treatment Committee recommended a conditional acceptance of biological treatment (fluidized bed reactor) for the removal of perchlorate in a drinking water supply. The recommendation is based on a treatability study of the full-scale FBR system treating perchlorate-contaminated groundwater at the Aerojet facility in

Rancho Cordova. Biological treatment systems are being considered by the Castaic Lake Water District as well as in the San Gabriel Groundwater Basin, but to date DHS has not issued a permit to any facility that allows biological treatment for domestic water supply.

Bioreactors: Fluidized Bed, Packed Bed, Fixed Film, etc.

- *Aerojet, Rancho Cordova.* Four Envirogen fluidized bed reactors (FBR) with GAC media have been in operation since 1998. The system was designed to treat 8 mg/l of perchlorate with a perchlorate loading of 44 lb/day per 1000 cubic feet of reactor volume. Each reactor has a design capacity of 1800 gpm. This system has been operating at about 3500 gpm (< 900 gpm each) treating concentrations of about 3500 µg/L to non-detect levels (<4 µg/L). Ethanol is used as the electron donor. The treated water is re-injected into the aquifer. GAC media (versus sand) was selected to assure a low concentration effluent. [The Aerojet System is based on pilot scale laboratory testing using a 30 gpm FBR developed by U.S. Filter and Envirogen. These results showed that perchlorate at concentrations from 4 mg/L to 400 mg/L could be reduced to < 4 µg/L. The pilot scale FBR also successfully reduced high concentrations of chlorate (480 mg/L) and nitrate (20 mg/L). Sand-based FBRs fed ethanol as an electron donor reduced all three chemicals below quantitation limits.]
- *Long Horn Army Ammunitions Plant, Texas.* A full-scale 50 gpm fluidized bed reactor developed by US Filter / Envirex and Envirogen with carbon media and acetic acid/nutrients additions was installed to treat perchlorate-contaminated groundwater. Extracted groundwater flowrate of 30 to 35 gpm with perchlorate concentrations up to 35 mg/L were being treated to meet the <350 µg/L target goal, and routinely to below the 5 µg/L limit of quantitation.
- *NASA, JPL Pasadena,* Foster Wheeler/ Arcadis Packed Bed Bioreactor. Pilot tests were conducted on several reactors. Results as of May 2001 indicate reactors can successfully treat low concentrations of perchlorate (< 1 mg/L) to non-detectable levels (< 1 µg/L).
- *NASA, JPL Pasadena,* US Filter-Envirogen Fluidized Bed Reactor (FBR). Pilot test using native "JPL bacteria" and ethanol as the food source successfully treated low concentrations of perchlorate (350 to 740 µg/L) to non-detectable levels (< 4 µg/L).
- *Thiokol, Brigham City, Utah.* Applied Research Associates implemented a full-scale biological system to treat industrial wastewater containing high concentrations of salt (>2%), nitrate, and perchlorate (>5,000 mg/L). This system discharges treated effluent to the sewer and has operated continuously since December 1997. Perchlorate concentrations in the treated effluent during 1999 ranged from 4 to 400 µg/L. Initial pilot scale work was performed by the Air Force Research laboratory at Tyndall AFB, Florida.
- *Kerr- McGee, Henderson Nevada*. Applied Research Associates, Inc. conducted numerous treatability studies to optimize conditions for treating perchlorate contaminated groundwater, and teamed with Biothane Corporation to complete a detailed engineering design for an 825 gpm suspended-growth, CSTR biological treatment plant. The design is to treat 400 mg/L (~4000 pounds per day) of perchlorate to a concentration below 4 µg/L that can be discharged under a NPDES permit. Not selected due to higher capital costs.
- *Crafton-Redlands Plume, Redlands, CA.*. Pennsylvania State University, funded by

the American Water Works Association Research Foundation (AWWARF), is conducting anaerobic packed bed reactor pilot scale tests, one with sand and one with plastic media. Initial results show both reactors with acetate and trace nutrient additions capable of reducing concentrations of 70 µg/L perchlorate to less than 4 µg/L. Prior to the pilot scale tests, Pennsylvania State University conducted perchlorate degradation studies in laboratory scale reactors evaluating both acetate-fed, packed bed reactors and hydrogen reactors.

- *EcoMat - Hall reactor*. A 2-stage biological treatment system, including the patented Hall reactor, was demonstrated at a Department of Defense facility in southern California with shallow groundwater contaminated with perchlorate. A 200 liter system installed on a 4 × 4 ft. skid was used to remediate perchlorate contaminated groundwater from environmental investigation work that was being stored in 20,000 gallon Baker tanks. Perchlorate concentrations were reduced from 350 µg/L to non-detectable levels. Methanol was used as the carbon (electron donor) source.
- *Applied Research Associates, Inc*. Tests were conducted with a bench scale version of a full-scale patented process on 5× and 10× reverse osmosis rejectate containing high total dissolved solids and up to 10 mg/L of perchlorate. The bench scale reactor was operated both as a fixed film process and as a suspended growth CSTR process. Perchlorate concentrations were biologically reduced to less than the 20 µg/L detection limit.
- Hollow-Fiber Membrane Biofilm Reactors. Bruce E. Rittmann of Northwestern University has developed and patented a hollow-fiber membrane biofilm reactor that utilizes hydrogen as the electron donor to biologically degrade perchlorate. He has teamed with Montgomery-Watson-Harza Engineers, Inc. to conduct a pilot study in La Puenta, Calif., treating groundwater that is highly contaminated with perchlorate and nitrate. Results have shown that the biofilm reactor can effectively treat 0.3 gallons of water per minute, removing perchlorate and nitrate at the same time.

Biologically Active Carbon (BAC)

AWWARF-funded bench and pilot scale tests indicate that biologically active carbon filtration can effectively remove low levels of nitrate and perchlorate under anaerobic conditions with the addition of an electron donor. Nitrate reduction can also enhance perchlorate reduction kinetics, making BAC filtration particularly attractive for combined nitrate-perchlorate remediation.

In Situ Biological Reduction

- Aerojet, Sacramento. GeoSyntec Consultants conducted a pilot test to accelerate in-situ bioremediation of perchlorate in a deep aquifer. The contaminated aquifer is approximately 90 feet thick and extends to 100 feet below ground surface. The system design was a closed groundwater recirculation loop where groundwater was extracted, then amended with acetate (electron donor) before being re-injected at an upgradient location. The pilot test design included one donor delivery well, one extraction well and two monitoring wells. Perchlorate concentrations up to 12 mg/L were reduced to below 4 µg/L within 15 feet of the donor delivery well in approximately 50 days. The biodegradation half-life was determined to range from 0.2 to 1.8 days.

- *Naval Weapons Industrial Reserve Plant, McGregor, Texas*. In-situ Biological Treatment of Groundwater. A 25 feet-deep groundwater collection trench constructed with composting materials, cotton seed meal and cotton seed. Results of the this pilot test along with supporting bench-scale test results indicated the capability to biodegrade perchlorate from 27,000 µg/L to below 4 µg/L.
- *NASA, JPL Pasadena.* An in-situ biological treatment pilot test is planned to be initiated during 2003 to test the viability of using in-situ bioremediation to reduce the concentration of perchlorate in the on-site source area**.** A workplan is under development. Arcadis is the consultant. Corn syrup is now being considered over molasses as the electron donor.
- *Edwards AFB.* Use of slow release edible oils developed by Solutions IES in an in-situ biological treatment permeable barrier system is being investigated.

Contaminated Soil - Composting

Naturally occurring bacteria can effectively reduce perchlorate under anaerobic conditions when perchlorate-contaminated soil is composted with an organic carbon source (electron donor) such as steer manure, sawdust, alfalfa, corn syrup, alcohol, sodium acetate, etc.

- *Aerojet, Sacramento, CA. G*eoSyntec Consultants conducted a pilot demonstration of anaerobic composting of soils from the former perchlorate burn area. The maximum detected perchlorate concentration in the burn area was 4200 mg/kg. Two approximately 10 cubic yard piles were treated from an average of about 23 mg/kg to about 0.1 mg/kg in seven days. The degradation half life was determined to be one to two days.
- *Long Horn Army Ammunitions Plant, Texas*. In-situ biological treatment of perchlorate contaminated soil was planned for completion in 2001. Bench scale results indicate that soils from LHAAP containing 350 mg/kg could be treated to non-detectable levels in less than 9 days.
- *Pueblo Army Depot, Colorado.* Composting was performed to remediate on soils contaminated with explosives (HMX and RDX). These soils are now known to contain perchlorate contamination. Analyses of treated soils are underway to assess the effectiveness of the composting process in reducing perchlorate concentrations.

GRANULAR ACTIVATED CARBON (GAC)

In general, aqueous-phase GAC has not been found to efficiently treat perchlorate. However, there are several facilities where GAC has been used to treat VOCs that have had success in treating perchlorate as a co-contaminant. The removal mechanism is probably a chemical reduction reaction that occurs on the surface of the carbon, similar to other oxidants such as chlorine, bromate, and chlorite that have been studied.

U.S. EPA and the AWWARF are funding research on enhancement techniques such as pre-loading with an iron organic complex and regenerating with an anionic reducing solution. A Penn State University study will utilize existing full-scale GAC units installed at a number of water treatment facilities that process perchlorate contaminated water. Column studies indicate that 40-45% more capacity may be achieved by pre-loading with an iron

organic complex, and that 50-74% of initial capacity could be restored by reducing regenerant solution.

- *Crafton- Redlands Plume, City of Redlands.* An activated carbon treatment system was initially installed to remove VOC contaminants from municipal water supply wells. The GAC system was later found to be effective in removing perchlorate when low concentrations of perchlorate (60 to 138 µg/L) were discovered. In September 2001, the Department of Health Services issued a domestic water supply permit amendment to the City of Redlands Municipal Utilities Department to operate the Texas Street GAC facility to remove perchlorate in their domestic water supply system. The GAC bed needs to be regenerated every 6 weeks for perchlorate treatment versus the 8 months that was required for treatment of the VOCs. Penn State University is using four of the twenty-four GAC vessels at the same facility for additional studies, looking at enhancing GAC performance by preloading with iron organic complex and regenerating with reducing solution.
- *Edwards Site 133.* A GAC system that was constructed in May 2001 to remove VOCs is now treating 92 µg/L perchlorate as a co-contaminant.

MEMBRANE FILTRATION

Membrane filtration technology such as reverse osmosis and nanofiltration are basically very fine filters that use a semi-permeable membrane to remove undesired dissolved ions in water. There is currently little available performance data on perchlorate removal using these technologies. The AWWARF is supporting an ongoing research project to investigate the feasibility of membrane filtration technology for perchlorate removal in water sources of different quality.

The primary drawbacks to membrane filtration technology would be the energy requirements and production of a brine, which can be as high as 15% to 20% of the groundwater volume treated. The brine containing high TDS and perchlorate concentrations would require treatment or proper disposal. Membrane fouling due to hardness or biological growth is another concern (silica, oil, clay, iron, sulfur and humic acids can be present in a very fine or colloidal form; calcium carbonate and calcium sulfate scaling present problems). Due to the high capital and O&M costs, membrane filtration technology may not be relatively cost effective.

Reverse Osmosis (RO). Water is forced through a semi-permeable membrane. RO has long been used to treat groundwater and other water sources to remove high concentrations of total dissolved salts. It would also be expected to be effective in removing perchlorate ions although there is limited performance data, if any, to support this conclusion. Unselective removal of dissolved ions results in a more corrosive, lower pH effluent. There may also be an issue with degradation of the membrane in treating perchlorate.

Nanofiltration. A partially permeable membrane is used to preferentially separate different fluids or ions. The membrane pores in nanofiltration are typically much larger than

the membrane pores that are used in reverse osmosis. Since it is not as fine a filtration process as reverse osmosis and requires less energy to perform the separation. Nanofiltration generally works for particle sizes over 10 angstroms (10^{-10} m), rejecting selected salts (typically divalent), and passing more water at lower operating pressure than RO systems. Based on the size of the perchlorate ion, about 3.5 angstroms, nanofiltration may not prove to be effective for perchlorate removal.

Electrodialysis. Water is passed through channels of alternating semi-permeable and permeable membranes (to either anions or cations), while being exposed to an electrical field. An electrodialysis reversal (EDR) pilot unit (7.4 gpm Ionics Aquamite III) was installed at an uncontaminated Magna Water Co. (Utah) well with high TDS (1300 mg/l) and silica (80 mg/l), and operated continuously for four days to evaluate perchlorate removal effectiveness. The extracted groundwater feed to the pilot unit was dosed to130 µg/L perchlorate. Test results indicate that perchlorate removal rates stabilized in the low 70 percent range and that higher removal rates (94%) could be achieved with a four stage system.

CHEMICAL REDUCTION

UV Light / Zero Valent Iron Reduction - Lab studies (Gurol, Mirat D., and Kyehee Kim, 2000) indicate that perchlorate can be reduced by iron (FeO) under anoxic conditions and that UV light can accelerate the reaction rate to levels for practical application. A patent (#6,531,065) was issued March 11, 2003. The patent also covers use of the iron metal with a catalyst and with phosphoric acid. As of June 9, 2003, the San Diego State University Foundation, Office of Technology Transfer, was seeking funds to commence six months of field testing to develop a commercial prototype.

Titanium +3 Chemical Reduction - Georgetown University has developed a technique using titanous ions (+3) to chemically reduce perchlorate. Several new organic ligands have been developed that have been shown to catalyze reduction of perchlorate by titanous ions (+3) ions to titanium dioxide and chloride in acidic aqueous media. A preliminary patent application has been filed.

Electrochemical Reduction - A bench scale study (AWWARF funded) of electrochemical reduction of perchlorate was conducted using two-chambered batch reactor systems. Cathodic and anodic compartments were separated by an ion exchange membrane, and electrodes consisted of titanium coated with a thin film of titanium dioxide particles. Initial perchlorate concentration ranged from 50 mg/L to 500 mg/l. Perchlorate reduction was limited due to the competition among anions for active sites on the electrode surface, with perchlorate being less strongly adsorbed than both sulfate and chloride. The time required for ions in the water to travel to the electrode surface is a design problem in developing a practical full scale system.

(Note: Several chemical reduction processes for perchlorate related to treatment of ion exchange brine are discussed under the section on ion exchange.)

PHYTOREMEDIATION

Plants are known to uptake salts such as perchlorate when irrigated with water or grown in soils containing elevated concentrations of such compounds.. Most notably, health concerns have recently been raised regarding reports of elevated concentrations of perchlorate in lettuce or other vegetables that have been irrigated with Colorado River water contaminated with perchlorate. Such properties in plants are under investigation as potential phytoremediation strategies:

- *Willow Trees*. In bench scale tests, willow trees successfully treated water contaminated with both perchlorate and TCE. Rhizodegradation accounted for most of the removal of perchlorate with little uptake into the plant. Plant uptake might be significant with high nitrate environments (a competing terminal electron acceptor).
- *Salt Cedar Trees*. Salt Cedar trees are known to mine salt from the water. Stalks of the plant in the Las Vegas Wash picked up significant concentrations of perchlorate per gram of tissue
- *Containerized Wetlands.* A Containerized Wetland System designed to remove nitrate and perchlorate from ground water was tested at Lawrence Livermore National Laboratory. The engineered use of plants to remediate water relies on the interaction of the contaminant with plant roots, and their associated rhizosphere microorganisms, to assimilate or degrade nitrate and perchlorate. The system consists of fiberglass tanks in series, which contain coarse aquarium-grade gravel and native wetland plants, such as bulrushes (Scripus), cattails (Typha) and sedges (Carex). The testing, conducted over a seven-month period, resulted in the removal of nitrate (as NO3 to <4 mg/L) and perchlorate (<4 µg/L).

REFERENCES

1. Roote, Diane S. "Technology Status Report, Perchlorate Treatment Technologies." 1st ed. Ground-Water Remediation Technologies Analysis Center, 2001.

2. Darrett, Michael; Touchi, Steven R. Perchlorate "Treatment Options for the Community Wellhead Treatment System Technical Memorandum, Revision 1.0" Department of Toxic Substances Control, March28, 2002.

3. Urbansky, E.T. and M.R. Schock, 1999. "Issues in Managing the Risks Associated withPerchlorate in Drinking Water", in Journal of Environmental Management, Vol. 56, pp. 79-95., Article No jema.1000.0274, available at http://www.idealibrary.com.

4. Urbansky, E. T. 1998 . ''Perchlorate chemistry: Implications for analysis and remediation.'' *Bioremed. J.*, 2(2), 81–95.

5. Logan, Bruce E. "Assessing the outlook for perchlorate remediation." *Environmental Science and Technology* 35 (2001): 482A - 487A.
(http://pubs.acs.org/subscribe/journals/esthag-a/35/i23/logan/23logan.html)

6. Interstate Technology Regulatory Council. *A Systematic Approach to In Situ Bioremediation in Groundwater Including Decision Trees on In Situ Bioremediation for Nitrates, Carbon Tetrachloride, and Perchlorate, Technical/Regulatory Guidelines*. August 2002. (http://www.itrcweb.org/user/isb-8r.pdf)

7. Communication with Ron Lewis, DTSC Stringfellow Branch on 2/11/03 re: perchlorate contamination Treatment Alternatives.

8. Communication with Leslie Ferry, LLNL on 4/2/03 re: perchlorate and nitrate groundwater treatment systems at Lawrence Livermore National Laboratory.

9. Communication with Sharon Wong, DHS Division of Drinking Water and Environmental Management on 2/25/03 re: drinking water systems approved for perchorate treatment.

RELATED LINKS ABOUT PERCHLORATE AND TREATMENT

Technologies General:

U.S. Environmental Protection Agency (EPA) Perchlorate Home Page
EPA Office of Water - Ground Water and Drinking Water
http://www.epa.gov/safewater/ccl/perchlorate/perchlorate.html

U.S. Environmental Protection Agency (EPA), Region IX Fact Sheet on Perchlorate
http://www.epa.gov/safewater/perchlorate/pdf/r9699fac.pdf

\CLU-IN.ORG Perchlorate Remediation Resources
http://www.clu-in.org/perchlorate

Defense Environmental Information EXchange (DENIX) -Public-Library-Water-Perchlorate-Treatment Technology
https://www.denix.osd.mil/denix/Public/Library/Water/Perchlorate/technology.html

Awwa Research Foundation Projects Related to Perchlorate
(list & project summaries only ; publications require membership)
http://www.awwarf.org/research/TopicsAndProjects/topicSnapShot.aspx?Topic=Prchlte

Perchlorate News: Perchlorate sites and the treatment of Perchlorate contamination
http://www.perchloratenews.com/index.html

Information and Resources About Perchlorate And Treatment Options
(Sponsored by Calgon Carbon Corp. – presents case studies from Ground-Water Remediation Technologies Analysis Center 2001 report)
http://www.perchlorateinfo.com/perchlorate-overview.html

Slide Presentation: Ammonium Perchlorate Treatment Technology Development
James A. Hurley, Program Manager Air Force Research Laboratory
http://www.epa.gov/safewater/perchlorate/pdf/hurley.pdf

Drinking Water Standards:

Dept. of Health Services. Perchlorate in California Drinking Water: Status of Regulations and Monitoring Results
http://www.dhs.cahwnet.gov/ps/ddwem/chemicals/perchl/perchlindex.htm

Anion Exchange:

Oak Rridge National Laboratory (ORNL) Highly Selective, Regenerable Anion Exchange Resins
http://www.esd.ornl.gov/~b26/ClO4.htm
http://www.esd.ornl.gov/~b26/ClO4-destruct.htm

Bi-functional Resin for Removal of Contaminants from Groundwater
Innovative Technology Summary Report DOE/EM-0634
http://apps.em.doe.gov/OST/pubs/itsrs/itsr255.pdf

Nitrate and Perchlorate Removal from Groundwater by Ion Exchange Pilot Testing and Cost Analysis
Lawrence Livermore National Laboratory, University of California UCRL-ID-135639
http://www.llnl.gov/tid/lof/documents/pdf/236620.pdf

Optimization Study of Nitrate and Perchlorate Removal by Ion Exchange
Environmental Restoration Division LLNL Fact Sheet
http://www-erd.llnl.gov/infopack/posters/HaldenBurge.pdf

Calgon Carbon Corp. ISEP® Ion Exchange Technology for Perchlorate
http://www.ionexchangeseparation.com/about/perchlorate.html

Francis J. Silva, March 1999. "Essentials of Ion Exchange" presented at the 25th Annual WQA Conference.
http://www.resintech.com/Content/TechArticles/Essential%20of%20Ion%20Exchange.pdf

Proposed City of Monterey Park (City) Delta Treatment Plant (Delta), Notice of Intent to Adopt a Negative Declaration, December 2002
http://www.wqa.com/pdfs/DeltaNoticeOfIntent.pdf

Water Technology, Volume 23, Number 11, November 2000, "Removing Nitrate by Ion Exchange"
http://www.enviroalternatives.com/waternitrate.html

Edwards AFB Pilot Test – ORNL Bifunctional Resin
http://www.edwards.af.mil/penvmng/documents/rts/2001/jun01/Jun01pg1.htm

JPL Pasadena, Perchlorate Treatment Pilot Tests (biological & ion exchange)
https://www.denix.osd.mil/denix/Public/Library/Water/Perchlorate/JPLFRTR/jplfrtr.html
http://yosemite.epa.gov/r9/sfund/overview.nsf/0/78584149433b1be58825660b007ee65a?OpenDocument#approach

Thermal Decomposition of Brines:

EPA ORD NCER - Hydrothermal/Thermal Decomposition of Perchlorate
http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/1261/report/

Membrane Filtration:

Technical Manual Water Desalination TM 5-813-8 September 1986, Department of the Army
http://www.usace.army.mil/publications/armytm/tm5-813-8/c-9.pdf

Electrodialysis Reversal (EDR) And Ion Exchange As Polishing Treatment For Perchlorate Treatment
Pilot Project for Magna Water Company, Salt Lake City, Utah
http://www.desline.com/articoli/3931.pdf

Biological Treatment:

Ammonium Perchlorate Biodegradation for Industrial Wastewater Treatment
ESTCP Cost and Performance Report ,June 2000
http://www.estcp.org/documents/techdocs/199710.pdf

April 2, 2002 DHS Letter: Conditional Acceptance of Biological Treatment (Fluidized Bed Reactors) For The Removal Of Perchlorate During Drinking Water Production.
http://www.safedrinkingwater.com/community/Aerojetletter040222.pdf

NASA-California Institute of Technology Jet Propulsion Laboratory, Anoxic FBR
http://www.perchlorateinfo.com/perchlorate-case-40.html

JPL Pasadena, Perchlorate Treatment Pilot Tests (biological & ion exchange)
https://www.denix.osd.mil/denix/Public/Library/Water/Perchlorate/JPLFRTR/jplfrtr.html
http://yosemite.epa.gov/r9/sfund/overview.nsf/0/78584149433b1be58825660b007ee65a?OpenDocument#approach

Henderson Nevada – Las Vegas Wash, Colorado River Contamination Problem:

EPA Region 9 Corrective Kerr McGee Chemical Corporation, Henderson Nevada
http://yosemite.epa.gov/r9/r9coract.nsf/facilities/49635B803347117C88256AC50075A3F4?OpenDocumen

Colorado River Basin RWQCB September 2002 Executive Officer's Report – Perchlorate Discussion
http://www.swrcb.ca.gov/rwqcb7/documents/eo_reports/eo_02-09-04.htm